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2000 Annual Progress Report

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Office of Transportation Technologies

VEHICLE SYSTEMS PROGRAMS

U.S. Department of Energy
Office of Advanced Automotive Technologies
1000 Independence Avenue S.W.
Washington, D.C. 20585-0121

FY 2000

Progress Report for the Vehicle Systems Programs

Submitted to:

Energy Efficiency Renewable Energy
Office of Transportation Technologies
Office of Advanced Automotive Technologies
Vehicle Systems Team

Robert Kost **Vehicle Systems Team Leader**

January 2001

ACKNOWLEDGEMENT

We would like to express our sincere appreciation to Argonne National Laboratory and Computer Systems Management, Inc. for their artistic and technical contributions in preparing and publishing this report.

In addition, we would like to thank all our program participants for their contributions to the programs and all the authors who prepared the project abstracts that comprise this report.

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I. Introduction

Vehicle Systems Programs

On behalf of the U.S. Department of Energy's Office of Advanced Automotive Technologies (OAAT), we are pleased to introduce the Fiscal Year (FY) 2000 Annual Progress Report for the Vehicle Systems Programs. This introduction serves to briefly outline the nature, progress, and future direction of the program.

The Vehicle Systems Programs is an over-arching effort that includes all advanced automotive technologies and promotes their integration into complete systems. The mission of the Vehicle Systems team is to facilitate deployment of competitive, consumer-acceptable propulsion subsystems for light vehicles (automobiles, light trucks, and SUV's) that, achieve significantly improved levels of fuel economy, comply with projected emission regulations and safety standards, and are capable of operating on domestically produced fuels. The Vehicle Systems Programs focused primarily on the:

- Development of required propulsion system technologies
- Validation of component and subsystem technologies through laboratory testing in the context of a vehicle system environment
- Validation of the achievement of the vehicle-level OAAT objectives

The goal of the Vehicle Systems Programs is to facilitate development of competitive, consumer-acceptable, automotive propulsion systems through the definition of technology requirements, and development and validation of necessary component technologies. Activities include the development and validation of advanced hybrid-electric vehicle propulsion systems, design and development of advanced modeling and evaluation tools, development of facilities for testing vehicle systems, and development of advanced automotive accessories to ensure that these systems can be made more efficient and can work with the advanced propulsion systems under development. The program supports the Partnership for a New Generation of Vehicles (PNGV), a cooperative research and development (R&D) partnership between the federal government and the United States Council for Automotive Research (USCAR), comprised of Ford Motor Company, General Motors, and DaimlerChrysler Corporation.

Future Directions

The main challenge of the Vehicle Systems Programs is to accurately predict performance of advanced propulsion systems in light passenger vehicles using advanced technology, having the potential to achieve OAAT objectives of high fuel economy and low emissions, and to use these predictions to establish performance targets for researchers developing components and subsystems for automotive applications. The Vehicle Systems Programs will:

- Continue to focus on testing component technologies and overall vehicle systems validation through both testing and computer modeling.
- Begin identification of technology requirements for incorporating PNGV-supported technologies in a future high-fuel-economy sport utility vehicle (SUV).
- By 2004, develop and validate propulsion subsystem technologies and validate OAAT-developed technologies that will enable the achievement of 80 mpg in test-bed six-passenger sedans that retain all the attributes of comparable competitive vehicles, including emission controls.
- By 2011, develop and validate the production feasible vehicle subsystem technologies that will enable the achievement of 100 mpg in test-bed six-passenger sedans emphasizing non-petroleum-based fuels and zero emissions, and retain all the attributes and features of competitive vehicles.

The following abstracts summarize in program projects, and provide an overview of the work being conducted to overcome the technical barriers associated with the development of competitive, consumer-acceptable propulsion subsystems for light vehicles.

Robert Kost
Team Leader, Vehicle Systems Programs
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II. NATIONAL RENEWABLE ENERGY LABORATORY SUPPORT

IIA. Vehicle Auxiliary Load Reduction

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Objectives

- Develop innovative techniques and technologies that will reduce the energy used for vehicle auxiliary loads, manage peak loads, and optimize climate control systems and strategies. The short-term goal is to reduce the amount of fuel use for vehicle air-conditioning by 50% compared with today's vehicles by developing cost-effective solutions in partnership with industry. The long-term goal is to work with industry to achieve a 75% reduction in air-conditioning fuel use through long-term R&D on technologies such as heat-generated cooling and component miniaturization

Approach

- Work with industry to research and develop innovative climate control strategies that will cost-effectively reduce the amount of fuel use for vehicle air-conditioning by 50% compared with today's vehicles
- Optimize vehicle climate control system using ADVISOR and SINDA/FLUINT to co-simulate system in an industry project
- Develop a sweating thermal comfort manikin that will simulate complex heat and mass transfer from vehicle occupants to predict occupant physiological and psychological responses to environmental conditions created by new cabin thermal comfort technologies and control systems

Accomplishments

- Completed infrared reflective glazing tests on DaimlerChrysler minivans and Ford Explorers and completed the ESX3 steady-state A/C model, which demonstrated the first stage of the vehicle integrated systems analysis process
- Experimentally and numerically evaluated the benefits of solar reflective glazing for sedans, minivans, and sport utility vehicles and demonstrated the value of a systems approach using integrated modeling to analyze technical options and synergistic benefits to OEM advanced engineering teams and platform groups
- Developed an overall design for the thermal manikin and experimentally demonstrated various skin heating and sweating concepts

- Developed a SINDA/FLUINT air-conditioning model with an integrated lump-capacitance cabin model to predict cabin cooldown including evaluation of heat-pipe instrument panel thermal rejection system

Future Directions

- Initiate a project with OEMs showing 50% reduction in fuel use for auxiliary loads
- Build a limb for the thermal comfort manikin
- Expand thermal comfort model for realistic geometry and variable subject dimensions
- Link SINDA/FLUINT transient A/C model with ADVISOR

Introduction

NREL has the lead responsibility with DOE's Office of Transportation Technologies (OTT) to research, assess, and develop vehicle auxiliary load reduction strategies.

The vehicles of today and tomorrow are in need of systems that reduce vehicle auxiliary load demands. For mid-sized vehicles, air-conditioning systems can increase NOx emissions by 80% and increase CO emissions by 70% while reducing fuel economy by 22%. Smaller and lighter climate control systems will not only reduce emissions but also reduce fuel consumption. Each 20-lb. reduction in weight leads to a 0.1-mpg increase in fuel economy.

NREL's Cool Car and Auxiliary Load Reduction Project Manager, Rob Farrington

Vehicles of the future, such as hybrid electric vehicles, will require advanced climate control technologies because they will have smaller sized engines that will not be able to handle peak air-conditioning loads or cabin heating requirements without serious fuel economy impacts.

Approach

NREL is conducting research and development with several industry partners including DaimlerChrysler, Ford Motor Company, Johnson Controls, Delphi, Visteon, 3M, Southwall, Denso, Valeo, and PPG.

NREL has developed a SINDA/FLUINT air-conditioning model with an integrated lump-capacitance cabin model to predict cabin cooldown. NREL is in the process of validating and improving a transient A/C code, which is linked to ADVISOR and will enable fuel economy and tailpipe emission predictions.

In addition, NREL experimentally and numerically evaluated the benefits of solar reflective glazing for sedans, minivans, and sport utility vehicles and demonstrated the value of a systems approach using integrated modeling to analyze technical options and synergistic benefits to OEM advanced engineering teams and platform groups. As part of this effort, NREL worked to complete infrared reflective glazing tests on DaimlerChrysler minivans and Ford Explorers and completed the ESX3 steady-state A/C model, which demonstrated the first stage of the vehicle integrated systems analysis process.

Since industry has indicated a need for a sweating thermal manikin, NREL completed the design and experimentally demonstrated various skin heating and sweating concepts for this one-of-a-kind manikin. A competitive solicitation for manikin construction has been issued. This thermal comfort manikin is a breakthrough technology that simulates complex heat and mass transfer from vehicle occupants to predict occupant physiological and psychological responses to environmental conditions created by new cabin thermal comfort technologies and control systems. It is needed to evaluate new concepts such as ventilated/cooled/heated seats, zonal conditioning, moisture removal from the occupant, solar reflective interior materials and glazing, radiant heating, and parked car ventilation techniques.

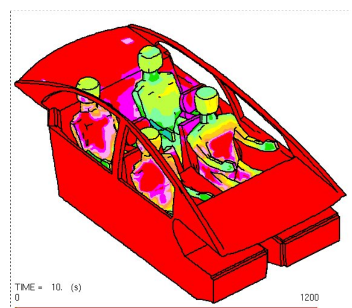
Thernal Manakin Used to Simulate Human Responses to Complex Environmental Conditions

Results

The Auxiliary Loads Team successfully tested three pairs of vehicles, including minivans and SUVs, with a team of U.S. OEMs and U.S. glazing suppliers. The results demonstrated the benefits of advanced glazing systems by reducing vehicle soak temperature by as much as 7 degrees C and cool-down time by several minutes. NREL staff modeled the impact of the reduced load of vehicle fuel consumption and tailpipe emissions.

Industry Collaborative Vehicle Testing of Advanced Climate Control Technologies

Industry experts gathered at NREL to discuss the state-of-the-art of advanced vehicle glazings and recommend future R&D needs. They identified modeling and analysis of advanced glazing systems as a critical need.



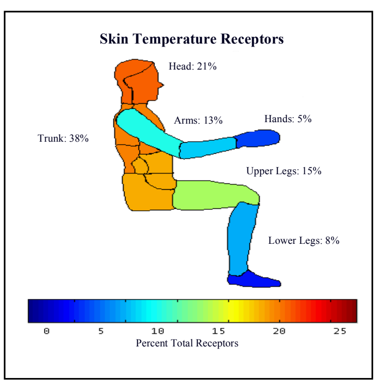
Computer Prediction of Occupant Temperatures Showing Benefits of Advanced Glazing

NREL worked with DaimlerChrysler and their suppliers to use integrated modeling that demonstrated the benefits of advanced climate control in DaimlerChrysler's ESX3 Hybrid Electric Vehicle. Various solar angles were modeled at different vehicle speeds to show the temperature and velocity fields in the vehicle. Advanced glazings significantly reduced the thermal asymmetry in the vehicle cabin from 31 degrees C to about 8 degrees C.

DaimlerChrysler's ESX3 HEV with Advanced Cabin Heating and Cooling Systems

NREL completed the preliminary design and began construction of a thermal comfort manikin to measure the impact of advanced climate control strategies in conventional and advanced vehicles on occupant comfort.

The state-of-the-art manikin will mimic human physiological responses to environmental conditions including temperature, air speed, and solar radiation. A computer model will control the manikin and predict occupant psychological response to the environment.



Distribution of Hot and Cold Receptors in a Human Body

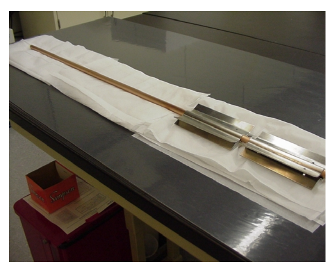
NREL completed construction of a heat pipe test loop to test advanced concepts to reduce vehicle soak temperatures using technologies that industry has identified as promising. Initial test results show that heat pipes can cool the instrument panel by nearly 20 degrees C.

Conclusions

NREL plans to initiate a project with OEMs showing 50% reduction in fuel use for auxiliary loads. NREL will also continue the effort to build the thermal comfort manikin and expand thermal comfort model for realistic geometry and variable subject dimensions.

In addition, linking SINDA/FLUINT transient A/C model with ADVISOR will be of high importance in FY2001. This will help optimize vehicle climate control system by using ADVISOR and SINDA/FLUINT to co-simulate system project in an industry project.

Work will also continue related to the evaluation of the miniaturization of components, porous media heat exchangers, heat-generated cooling concepts such as metal hydride heat pumps, and cabin heat pipe thermal rejection systems.



Heat Pipe Used to Efficiently Transport Heat

Presentations/Publications

"Opportunities to Reduce Air-Conditioning Loads Through Lower Cabin Soak Temperatures." Technical Paper at EVS16. R. Farrington, M. Cuddy, M. Keyser, and J. Rugh (Oct. 1999).

"Opportunities to Reduce Air-conditioning

Loads Through Lower Cabin Soak Temperatures." Published by the Technical Association of Automobiles in Italy. (October issue, Vol. 52, number 10). R. Farrington, M. Cuddy, M. Keyser, and J. Rugh (Oct. 1999).

"Innovative Techniques for Decreasing Advanced Vehicle Auxiliary Loads." Technical Paper prepared for FutureCar 2000. John P. Rugh, René S. Howard, Robert B. Farrington, Matthew R. Cuddy, Daniel M. Blake (April 2000).

"Effect of Solar-Reflective Glazing on Fuel Economy, Tailpipe Emissions, and Thermal Comfort." Technical Paper prepared for IBEC 2000. J. Rugh, R. Farrington, and G. Barber (Oct. 2000).

"ICE3: Innovative Climate-controlled Cabin Environments." Published in Automotive and Transportation Interiors December 1999 issue as well as on their Web site at *http://www.autointeriors.com/dec99stor2.htm.*

IIB. Vehicle Systems Analysis

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Objectives

- The goals of NREL's Vehicle Systems Analysis activities are to:
  - further improve, validate and apply NREL's advanced vehicle modeling capabilities in ADVISOR
  - improve vehicle optimization capabilities
  - establish co-simulation between ADVISOR and Saber
  - help industry weave improved fuel economy and emissions into future production components and vehicles through the Digital Functional Vehicle process

Approach

- Use specifications from a variety of component suppliers and original equipment manufacturers to expand ADVISOR and ensure that the information in the ADVISOR component and vehicle database is validated by industry, NREL, and ADVISOR users
- Continuously keep ADVISOR users informed of changes and improvements to the tool through the Web site, user group discussions, and simulation modeling conferences

Accomplishments

- ADVISOR (versions 2.2.1 and 3.0) advanced vehicle simulator was released to the public through the NREL Web site. Over 2700 people from around the world have now downloaded at least one version of the ADVISOR software
- Held the ADVISOR User's conference on Aug. 24-25, 2000 with 65 attendees from around the world
- Made significant progress on creating a common GUI to run both ADVISOR and PSAT
- Completed phase 1 work on the Digital Functional Vehicle project with PTC; initiated contract with MDI and began the second phase of work: applications with industry
- Conducted an analysis of the viability of "grid-connected" or wall-charge hybrid electric vehicles using ADVISOR as part of an industry-government consortium

Future Directions

- Further improve, validate, and apply ADVISOR to satisfy the needs of DOE, the auto industry, and the 2700 ADVISOR users

- Continue to push the envelope in the field of optimization while also focusing on application to hybrid vehicles and general applicability to multiple software codes
- Complete co-simulation between ADVISOR and Saber for 42V conventional vehicles and apply to a real problem
- Demonstrate success with MDI on 2-3 specific vehicle applications in the auto industry to demonstrate the Digital Functional Vehicle process

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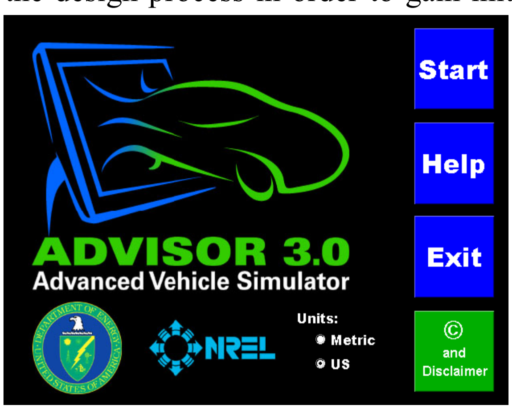
Introduction

In 1994, the National Renewable Energy Laboratory (NREL) created the ADvanced VehIcle SimulatOR (ADVISOR) through the DOE Office of Transportation Technologies (OTT). ADVISOR's goal is to help the automotive industry model vehicle systems using computer tools to supplement building and testing the systems. NREL has expanded the tool's capabilities over time, and now has an easy-to-use interface, pull-down menus, improved results screens, validated component information, and many vehicle system designs to choose from. ADVISOR can be downloaded free of charge from the Vehicle Systems Analysis Web site (www.ctts.nrel.gov/analysis). More than 2700 users from around the world have downloaded the software to evaluate vehicle systems and various vehicle configurations.
In the past, vehicles were designed and tested using hundreds of hardware prototype vehicles. Complete vehicles were built early in the design process in order to gain initial data on the design, and this process was repeated multiple times. ADVISOR helps to solve this problem and provides an opportunity to reduce time to production.



Introduction screen for ADVISOR 3.0

Approach

Quickly gaining an understanding of an advanced vehicle design's sensitivity to change is a major benefit of using a tool like ADVISOR early in the vehicle design process. Improving the time to production and saving money are both important benefits to using simulation tools. In addition, ADVISOR uses specifications from a variety of component suppliers and original equipment manufacturers. The information in the ADVISOR component and vehicle database is validated by industry, NREL, and ADVISOR users. Although auto manufacturers have similar in-house tools, ADVISOR provides an objective standard through which the companies can simulate vehicle performance and emissions benefits using components developed by many different suppliers.

Results

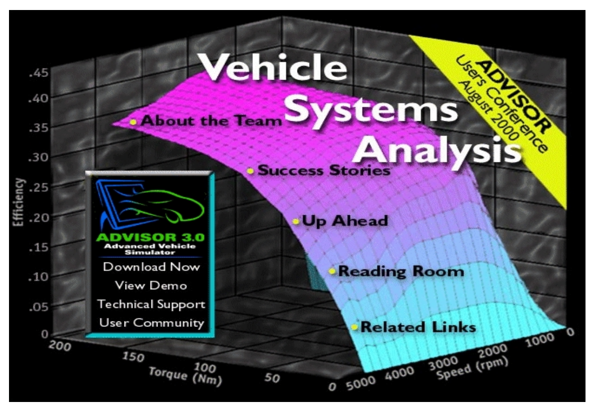
Since ADVISOR (versions 2.2.1 and 3.0) advanced vehicle simulator was released to the public through the NREL Web site, more than 2700 people from around the world have downloaded the software. This allows more people to have free access to state-of-the-art hybrid vehicle data and an easy to use model to execute vehicle simulations. This has a significant impact on increasing the level of knowledge people have about hybrid vehicles in the auto industry OEMs, their suppliers, academia, and small businesses (that otherwise might not be able to afford to buy such a model).

ADVISOR team leads panel discussion at the ADVISOR User Conference

In addition, NREL conducted an analysis of the viability of "grid-connected" or wall-charge hybrid electric vehicles using ADVISOR as part of an industry-government consortium. From the analysis, we concluded that this HEV concept has benefits in terms of fuel economy and emissions over both conventional drive-train vehicles and the HEVs currently being produced. This analysis has increased the awareness of the hybrid configuration options possible to everybody involved, including EPRI, CARB, DOE, and the auto industry. The study also showed that battery cost is still the main issue, as it is for pure EVs, and that continued funding in this are is needed if these vehicles are to become viable.

NREL's Honda Insight undergoes testing at ETC

In order to benchmark HEVs, the ADVISOR team instrumented a Honda Insight HEV and tested it on a chassis dynamometer. NREL measured fuel economy, emissions, and battery performance. NREL will soon be able to validate its computer model of this vehicle, and then release it to the public in the ADVISOR Program. This vehicle model, along with the Toyota Prius model previously completed, allows the auto industry to benchmark the current state of the technology so that they know how to improve upon it. Another impact for DOE is that it gives them more technical data on what has been accomplished in these vehicles so that they can use it as a benchmark against the targets in their own R&D programs.



ADVISOR is available from NREL's web site as a free download

Conclusions

NREL will continue to further improve, validate, and apply ADVISOR to satisfy the needs of DOE, the auto industry, and the 2700 ADVISOR users. This will involve continuing to push the envelope in the field of optimization while also focusing on application to hybrid vehicles and general applicability to multiple software codes.

The co-simulation between ADVISOR and Saber for 42V conventional vehicles will be completed and applied to a real problem. Finally, to demonstrate the Digital Functional Vehicle process NREL will work with MDI on 4 specific vehicle applications in the auto industry and share results from the process publicly.

Presentations/Publications

"HEV Control Strategy for Real-Time Optimization of Fuel Economy and Emissions," Johnson, V., Wipke, K., Rausen, D., DOE 2000 Future Car Congress.

"Neural Network Based Battery Modeling for Hybrid Electric Vehicles," Bhatikar, S., Mahajan, R., Wipke, K., Johnson, V., DOE 2000 Future Car Congress.

"Validation of ADVISOR as a Simulation Tool for a Hybrid Electric Fuel Cell Vehicle," Ogburn, M., Nelson, D., Wipke, K., DOE 2000 Future Car Congress.

"Progress on Seamless Integration of Modeling Tools for the Digital Functional Vehicle" Wipke, K., Brooker, B., Sprik, S., Markel, T., NREL Report, September 2000.

"Expanding Breadth of Data/Models in ADVISOR," Vehicle Systems Analysis Team. NREL Report,
September 2000.

"Increasing the Utilization of ADVISOR and Holding the First ADVISOR Users Conference," Vehicle Systems Analysis Team. NREL Report, September 2000.

"Benchmarking ADVSIOR Modeling Capability Against Four Available State-of-the-Art Vehicles: Prius, Insight, Ford Hybrid, DaimlerChrysler Hybrid," Vehicle Systems Analysis Team. NREL Reports, September 2000.

IIC. Battery Thermal Management

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Objective

- To improve the thermal management of battery packs for electric and hybrid electric vehicles and extend the life and improve the performance of the packs

Approach

- Assist the auto industry with the thermal design and management of battery packs
- Develop battery models for various types of vehicle simulation tools such as ADVISOR
- Use a unique calorimeter to measure heat generation of batteries. Infrared thermal imaging, flow visualization, and thermal analysis and computational fluid dynamics are all used to assess and evaluate batteries
- Evaluate a variety of batteries for benchmarking purposes

Accomplishments

- Directed a subcontract with the University of Toledo to develop a working prototype “battery management system” for HEVs that could be packaged to achieve 75% less volume and mass, with better features and functions than existing HEV battery management
- Achieved higher quality results by improving the accuracy of the calorimeter to below +/-3% and reduced noise level on the calorimeter response to allow for measurement of self-discharge of battery modules
- Evaluated thermal characteristics of Plastic Li-Ion cells from High Energy Technology, Nickel Zinc from Evercel, Ovonic NiMH EV and HEV modules. Measured self-discharge power loss of an Ovonic EV module
- Developed ADVISOR temperature-dependent battery models for Ovonic NiMH EV, Evercel NiZn, Hawker lead-acid, and a capacitive model for SAFT high power lithium ion modules
- Evaluated the battery pack thermal management systems of the Honda Insight and Toyota Prius

Future Directions

- Continue to collaborate with industry to improve thermal management systems, develop battery models for vehicle simulations, and develop battery management systems
- Characterize thermal properties (heat capacity, heat generation rate, and thermal images) of cells and battery modules. Collaborate with PNGV program participants in this area (SAFT, PolyStor, etc.)
- Evaluate and test thermal behavior of HEV battery packs (Varta, Ovonic, Prius)
- Improve the current ADVISOR battery model by including both capacitance and resistance features of the battery and to be PNGV-PSAT compatible

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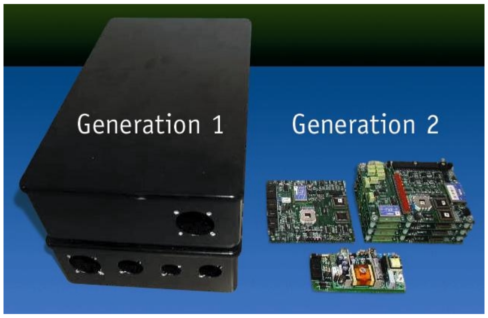
Introduction

The National Renewable Energy Laboratory (NREL) has the lead responsibility to evaluate and assess battery thermal management systems. This task is important because without proper battery thermal management, the temperature variation from one battery to another will affect battery electrical performance, and thus the vehicle performance. Understanding the thermal properties and behavior of batteries and packs will lead to improved battery performance. Developing validated battery models for use in the ADVISOR vehicle simulator leads to the identification of battery technologies that offer best performance in different hybrid vehicles.



Approach

As part of the U.S. Department of Energy's Hybrid Electric Vehicle Program, the National Renewable Energy Laboratory (NREL) assists the auto industry with the thermal design and management of battery packs. NREL has also developed several battery models for various types of vehicle simulation tools such as ADVISOR. In addition, NREL uses a unique calorimeter to measure heat generation of batteries. Infrared thermal imaging, flow visualization, and thermal analysis and computational fluid dynamics are all used to assess and evaluate batteries.

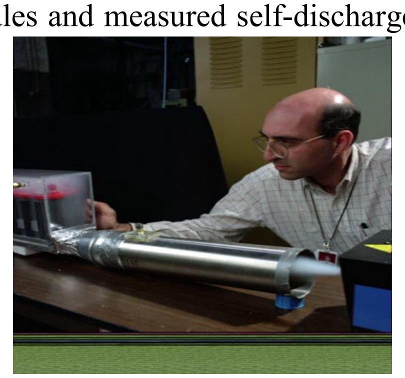
NREL uses its battery testing equipment to generate data and develop validated battery models. These models are then used in vehicle simulators to evaluate their impacts on vehicle performance. NREL continues to strengthen its relationship with auto manufacturers and suppliers by assisting with battery design needs and modeling. NREL's Battery Thermal Management and Modeling Project works hand-in-hand with industry to evaluate batteries and offer design improvements for modules and packs.

Results

This year, with support from an industry review committee including DaimlerChrysler, NREL directed a subcontract with the University of Toledo to develop a working prototype "battery management system" for HEVs that could be packaged to achieve 75% less volume and mass, with better features and functions than existing HEV battery management. This modular battery management system can help auto manufacturers, battery manufacturers, and battery pack integrators improve performance of HEV battery packs and achieve optimum energy efficiency in hybrid vehicles. NREL developed a prototype modular battery management system (Generation 2), which exceeded the initial project objectives. Compared to the first generation of the battery management system, the new prototype uses integrated circuitry and printed circuit board for volume, mass, and cost reduction. In addition, volume was reduced by 87% (exceeding the goal of 75% reduction) and mass was reduced by 70% (exceeding the goal of 50% reduction). The cost is expected to be 25% of the initial system, but could be reduced even more with its architecture. Several manufacturers have expressed interest in the next phase of the project, which is development toward eventual commercialization.

In addition, NREL worked to improve the accuracy of the calorimeter to below +/-3%. NREL reduced the noise level on the calorimeter response to allow for measurement of self-discharge of battery modules. These accomplishments are important for achieving high quality results.

NREL also evaluated the thermal characteristics of Plastic Li-Ion cells from High Energy Technology, Nickel Zinc from Evercel, Ovonic NiMH EV and HEV modules and measured self-discharge power



Dr. Pesaran uses advanced smoke tests to determine airflow distribution within battery packs/cells

loss of an Ovonic EV module. In addition, evaluated Li-Ion cells from CompactPower in collaboration with SMUD.

Working to help improve ADVISOR, NREL developed ADVISOR temperature-dependent battery models for Ovonic NiMH EV, Evercel NiZn, Hawker lead-acid, and a capacitive model for SAFT high power lithium ion modules.

Conclusions

NREL will continue to collaborate with industry to improve thermal management systems, develop battery models for vehicle simulations, and develop battery management systems.

This year, NREL will characterize the thermal properties (heat capacity, heat generation rate, and thermal images) of cells and battery modules. Collaboration with PNGV program participants will be important for this effort.

NREL will also evaluate and test thermal behavior of HEV battery packs (Varta, Ovonic, Prius) and work to improve the current ADVISOR battery model by including both capacitance and resistance features of the battery and to be PNGV-PSAT compatible.

In addition, NREL will continue to collaborate with University of Toledo and our industrial partners to test and improve the developed prototype modular battery management system for hybrid vehicles.

Presentations/Publications

"Charging Algorithms for Increasing Lead Acid Battery Life for Electric Vehicles," M. Keyser, A. Pesaran, and Bob Nelson. The 17th Electric Vehicle Symposium, Montreal, Canada, October 16-18, 2000.

"Temperature-dependent Battery Models for High Power Li-Ion Batteries," by V. Johnson, A. Pesaran, and T. Sack. The 17th

Electric Vehicle Symposium, Montreal, Canada, October 16-18, 2000.

"Developing Temperature-dependent Battery Models for ADVISOR," V. Johnson, M. Keyser, M. Mihalic, M. Zolot, and A. Pesaran. NREL Report, September 2000.

"Evaluating Battery Pack Thermal Management Systems from Four Hybrid Vehicles," A. Pesaran, M. Keyser, M. Zolot, and M. Mihalic. NREL Report, September 2000.

"Thermal Characterization of Advanced Battery Technologies for EV and HEV Applications," Matthew Keyser, Ahmad Pesaran, Mark Mihalic, Matthew Zolot. NREL Report, August 2000.

III. ARGONNE NATIONAL LABORATORY SUPPORT

IIIA. Advanced Powertrain Test Facility (APTF) New Installations

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Objective

- Conduct energy efficiency and emission tests on hybrid electric vehicles, sport utility vehicles, and future advanced- technology vehicles. These tests require a state-of-the-art electric four-wheel-drive chassis dynamometer with appropriate controls and instrumentation for highly accurate emissions and fuel measurements

Approach

- Obtain professional engineering/architectural services to assist with the preliminary design and construction documents for a world-class facility capable of benchmarking and developing the most advanced powertrains for future cars and trucks. The facility will be capable of hydrogen-fuel operation and will have the capability to add climate-controlled testing in the future
- To have highly sensitive emissions measurement equipment capable of SULEV (super ultra low emission vehicle) standards and a full dilution tunnel for diesel particulate matter measurement to enable complete diesel emissions measurement capability

Accomplishments

- Excel/Pierburg fast-response fuel scale was cleaned, calibrated, installed, and tested for proper operation
- Constant volume sampler (CVS) that will allow TLEV, LEV, ULEV, and SULEV vehicle testing was ordered from Pierburg and has been installed and calibrated in December 2000
- Four-wheel-drive chassis dynamometer was procured from Burke-Porter Machine Company after an extensive competitive bidding process
- Test cell design was completed and the building foundation finished in December 2000

Future Direction

- Focus on the design, procurement, and commissioning of the equipment to complete the 4WD facility to make it operational in the last half of 2001

Introduction

Argonne National Laboratory (ANL) has a lead responsibility for a PNGV-related program with DOE's Office of Transportation Technologies (OTT) to conduct emission and energy efficiency tests on hybrid-electric vehicles, sport utility vehicles, and future advanced-technology vehicles. These tests require a state-of-the-art electric four-wheel-drive chassis dynamometer with appropriate controls and instrumentation for highly accurate emissions and fuel measurements.

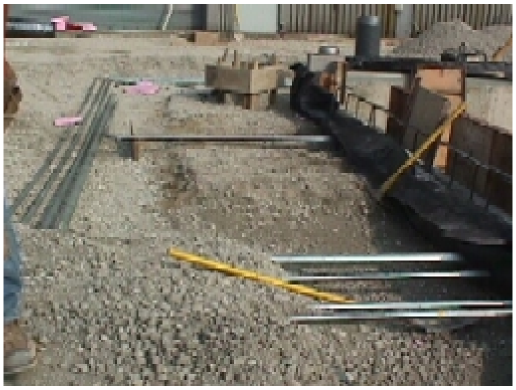
Approach

Argonne's APTF is an integrated test facility capable of testing powertrain components and vehicles by means of state-of-the-art measurement equipment and control hardware. Two component dynamometers, a 2WD chassis dynamometer, and a 4WD dynamometer (FY01) share extensive emissions and fuel consumption measurement equipment, including specialized equipment, to support advanced vehicle component testing. A 150-kW battery tester/emulator was installed to allow testing of hybrid-electric vehicle (HEV) battery packs and electric motors, as well as to allow simulating battery pack performance, thereby enabling repeatable tests of HEV powertrains. Argonne conducts vehicle and component-level testing of commercially available and OAAT-developed HEVs to characterize and enhance these technologies and to help evolve and validate the PSAT and ADVISOR simulation models. These components can then be configured as one or more complete powertrains and operated over standard or custom driving cycles. With the help of the APTF, better, more accurate models and more advanced control strategies will be developed. ANL's Energy Systems/Center for Transportation Research staff obtained professional engineering /architectural services to assist with the preliminary design and construction documents for a world-class facility capable of benchmarking and developing the most advanced powertrains for future cars and trucks. To make this new facility useful, sensitive emissions measurement equipment for SULEVs (super ultra low emission vehicles) was included (along with a full dilution tunnel for particulate matter measurement), enabling complete diesel emissions testing capability.

Results

Argonne's APTF underwent periods of construction for such items as upgraded electrical and lighting, warning beacons for unsafe entry, a gas monitoring safety system in the control room, and the building shell to house the 4-WD dynamometer. The Pierburg emissions bench and the Sierra Micro-dilution particulate-measuring mini-dilution tunnel were commissioned. The 2WD dynamometer data acquisition and the driver speed trace display was integrated with all the emissions test systems to perform standard FTP tests with high-speed emissions data collection of the Toyota Prius, the Honda Insight, and the P2000.

Argonne's APTF team wrote, revised, and received approval on safety and QA plans to ensure safe operation of facility and equipment. Two bids from major



Dynamometer Pit Near Completion

dynamometer manufacturers for the 4WD chassis dynamometer were received in December. ANL engineers, procurement specialists, and an external consultant evaluated the proposals. The 4WD contract was awarded to Burke-Porter. The fabrication of the chassis dynamometer was about half finished by the end of September. Preparations for both the commissioning at Burke-Porter and shipping of the dynamometer have begun. The dynamometer will be installed in the pit as soon as the test cell building is ready. Significant progress has been made in the construction of the 4WD chassis dynamometer. The concrete and I-beams for the dynamometer pit have been laid, and the building footings have been set.

The Excel/Pierburg fast-response fuel scale was cleaned, calibrated, installed, and tested for proper operation. This system will provide faster response and more accurate data than the system it is replacing at the APTF test stand.

A constant volume sampler (CVS) that will allow TLEV, LEV, ULEV, and SULEV vehicle testing was ordered from Pierburg. After evaluations by several engineers, it

Underground Conduits Being Set

was deemed that the system will work with our existing Pierburg emissions measurement bench and a possible future second-generation Pierburg bench. The bench will be installed and calibrated in December.

Conclusions

Construction of the extension to the current APTF building to house the 4WD chassis dynamometer cell and a vehicle soak area will be completed this spring. The chassis dynamometer and emissions equipment to support the current facilities and the 4WD chassis dynamometer, including an SULEV-capable Pierburg Emissions Bench and CVS will be installed and commissioned. The nephelometer (real-time particulate measurement) system will be completed, capabilities validated, and installed. Cross facility validation will continue by comparing the results of tests performed at APTF with those of identical tests performed at established auto industry test facilities. Beyond FY01, construction projects will be undertaken to install and calibrate equipment for the 4WD chassis dynamometer including additional specialized exhaust emissions equipment and capabilities to compliment the APTF. ANL also plans to build a climate control chamber for the 4-wheel drive dynamometer facility, to extend its usefulness to DOE and industry.

IIIB & IIIC. Engine and Component Mapping

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Objectives

- Determine the potential of HEV powertrain technology to achieve the technical goals for improved energy efficiency and reduced exhaust emissions by testing powertrain components using state-of-the-art measurement equipment and control hardware
- Investigate combinations and configurations of components that could lead to achieving the 80-mpg PNGV and future DOE energy efficiency improvement goals

Approach

- Two component dynamometers are available for testing
- Support equipment for the component dynamometers enable precise measurements for testing engines, transmissions, and advanced electric motors
- All test cells in the building share extensive exhaust emissions, fuel consumption measurement equipment, and include a 150-kW battery tester-emulator

Accomplishments

- ES/CTR has conducted component-level testing of commercially available and OAAT-developed HEVs to characterize and enhance these technologies. Components include a 45-kW Unique Mobility motor, the Honda Insight NiMH battery, and an NGM axial flux electric motor
- Test data have also helped to evolve and validate the DOE vehicle simulation models PSAT and ADVISOR
- Data were incorporated in the systems models to simulate advanced vehicles operated over standard and custom driving cycles to study vehicle and powertrain efficiency and exhaust emissions characteristics

Future Directions

- APTF plans to continue testing high-efficiency electric motors, engines, transmissions, and vehicles, paying particular attention to powertrain control strategy development for increased fuel economy and reduced emissions

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Introduction

The Advanced Powertrain Test Facility (APTF) in ES/CTR (Energy Sciences Division Center for Transportation Research) is an integrated test facility capable of testing powertrain components by using state-of-the-art measurement equipment and control hardware. The APTF is the main DOE facility for advanced and Hybrid-Electric Vehicle (HEV) technology assessment.

Objective

ANL's objectives are to evaluate, test, map, and benchmark HEV components and powertrains; help develop, validate, and improve HEV component and system models; and demonstrate and validate HEV powertrain performance potential in a system context.

Approach

The two component dynamometers are available for testing. The support equipment for the component dynamometers enable precise measurements for testing engines, transmissions, and advanced electric motors. All test cells in the building share extensive exhaust emissions and fuel consumption measurement equipment and include a 150-kW battery tester-emulator.

Results

Reports on Prius engine testing and a new Geo engine map were available, and the data were incorporated into PSAT and ADVISOR. A Toyota Prius Data Exchange Workshop hosted by ANL took place at USCAR in October 1999. The workshop was well received by the 42 government and industry participants. Argonne made presentations on the vehicle emissions, in-situ engine mapping, and the HEV control system and strategy used. A paper entitled "In-Situ Mapping and Analysis of the Toyota Prius HEV Engine" was prepared for the SAE Future Transportation Technologies Conference in August. This paper described the novel in-vehicle engine testing work at ANL and showed transient emissions results that are particularly interesting to the test and measurement community, because the Prius engine shuts down fuel and stops spinning during the test cycles.

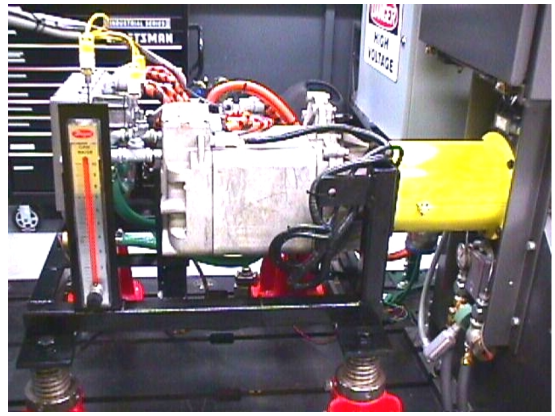
In cooperation with ANL's National Battery Test Laboratory, data from testing the battery pack from the Toyota Prius (NiMH) was obtained. Tests were performed for various other electric machines, including AC and DC traction motors, and generators of various sizes, including the New Generation Motors (axial flux motor), as well as other motors of interest to OAAT. ANL continues to work on a project to modify the controls of a Nissan Continually Variable Transmission (CVT) for HEV use and improve its efficiency by using an electrically driven oil pump. The component will be tested for performance and efficiency map data. Fabrication for mounting the CVT to a portable test bed was completed. The test bed was relocated adjacent to the APTF test stand, and then the supporting electrical and plumbing were completed.

The 45-kW Unique Mobility Motor was tested at five distinct voltages and in both directions of rotation under power and regeneration (all four quadrants of operation). The data was post-processed, and a detailed test report was written and submitted.

The P2000 will be used for validation of PSAT. Also, using the PSAT-PRO software the actual vehicle controller will be used as the controller for PSAT. This will further help validate the PSAT-P2000 vehicle model. The Science Lab in Dearborn, Michigan, disassembled the Ford P2000 powertrain, which has a damaged flywheel/rotor assembly of the starter/alternator system. Ford engineers are working to solve this design flaw. The DIATA engine was also disassembled at Ford. It was cleaned and inspected for wear during this downtime. The thrust bearings on the crankshaft were replaced as were critical gaskets. Modifications are also being made to the battery enclosure in the vehicle because of battery defects. The P2000 is expected to be back at ANL in December 2000, and vehicle testing will begin.

The Siemens electric motor will be tested to help populate PSAT with another electric motor model. This motor is also of interest for possible use in a high performance, post transmission, parallel hybrid. The Siemens Electric motor and accessories were mounted to a single cradle and then installed onto the bedplate of the new AC dynamometer located in test cell #2. Final alignment of the motor to the cradle was completed. The driveline adapters, coupling, and the driveline safety guarding were also completed. Work continues on the signal and control wiring. Ford staff will be visiting ANL in December 2000 to train operators on the operation of the drive. Testing will begin when (1) the schedule in the CIDI test cell allows and (2) the commissioning and personnel training of the dynamometer, control, and data acquisitions systems are complete.

The Honda Insight NiMH battery data collected by CMT were provided to Argonne's APTF group. The data collected by CMT will be used to validate the systems model that includes the Prius battery model. The data must remain proprietary and must not leave ANL without Panasonic/Matsushita's (PEVE) written permission. In addition, if battery characteristics can be estimated from the derived parameters, the data will remain proprietary.



Siemens Electric Drive Under Test

Preliminary testing continues with the NGM axial flux electric motor. Communications with NGM revealed several issues as to possible reasons why motor operation was sporadic. Initial concerns dealt with noise in the control signals. However, the fault in the system was traced to the current draw of the motor. During low-speed operation, the motor was drawing much greater instantaneous current than the documentation stated. The regulation of the voltage by the ABC-150 during these large current spikes caused a voltage fault in the controller that disabled the system. To finish testing the motor, a PbA battery pack operating at bus voltage was installed in the test cell.

Conclusions

The APTF plans to continue testing high-efficiency electric motors, engines, transmissions, and vehicles paying particular attention to powertrain control strategy development for increased fuel economy and reduced emissions.

Publications/Presentations

Duoba, M.J., et al., 2000, "In-Situ Mapping and Analysis of the Toyota Prius HEV Engine," *2000 Society of Automotive Engineers International Future Transportation Technology Conference*, Costa Mesa, CA, August 21–230

IIID. Vehicle Testing

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Objective

- Determine the potential of HEV powertrain technology to achieve the technical goals for improved energy efficiency and reduced exhaust emissions by testing vehicles using state-of-the-art measurement equipment and control hardware

Approach

- 2WD chassis dynamometer and a 4WD dynamometer (FY01) are available for vehicle testing
- All test cells in the building share extensive exhaust emissions and fuel consumption measurement equipment

Accomplishments

- ES/CTR has conducted vehicle testing of commercially available and OAAT-developed HEVs to characterize and enhance these technologies. Vehicles include the Toyota Prius, Mercedes 1.7 L, and the Honda Insight
- Test data have also helped to evolve and validate the DOE vehicle simulation models PSAT and ADVISOR

Introduction

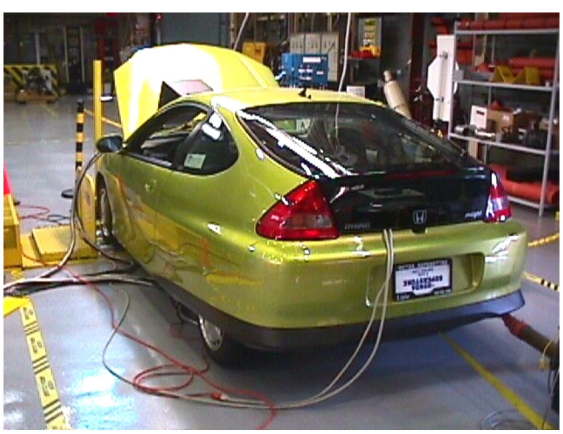
The Advanced Powertrain Test Facility (APTF) in ES/CTR is an integrated test facility capable of testing vehicles by using state-of-the-art measurement equipment and control hardware. The APTF is the main DOE facility for advanced and Hybrid-Electric Vehicle (HEV) technology assessment.

Approach

A 2WD chassis dynamometer and a 4WD dynamometer (FY01) are available for vehicle testing. The support equipment for the component dynamometers enable precise measurements for testing engines, transmissions, and advanced electric motors. All test cells in the building share extensive exhaust emissions and fuel consumption measurement equipment, including a 150-kW battery tester-emulator.

Results

ANL took delivery of two 1998 model-year Toyota Prius hybrid-electric vehicles for testing and assessment in ANL's Advanced Powertrain Test Facility. The Prius had been tested earlier by EPA in its laboratory in Ann Arbor, Michigan, with some involvement with Toyota before the ANL effort began. The focus of the ANL testing was not to reproduce the EPA results or provide detailed fuel economy or performance data of the vehicle; it was to support DOE's modeling efforts and to map the engine for efficiency and emissions. Moreover, the data from EPA was used as a benchmark to compare with data taken at ANL. ANL instrumented both Prius vehicles with up to 16 channels of signals monitoring each vehicle's systems, such as speed and braking and the main powertrain components: the engine, battery, generator, and main electric motor. One of the Prius vehicles was modified to accept a short-length torque sensor that allowed accurate torque and speed measurements to be taken while the vehicle is running on a chassis dynamometer. Several control laws were identified, and data streams from on-road and chassis dynamometer testing showed component speeds and relative power usage among the three mechanical power devices.



Honda Insight Testing Using ANL Chassis Dynamometer

The engine was mapped while in the vehicle by using a novel in-situ torque measurement approach that required installation of a short-length torque sensor and a significant reworking of the drivetrain and front frame rails. Prius engine peak thermodynamic efficiency was measured to be 36.4% at 2763 RPM and 85 N-m. Engine efficiency never went below 25% during the steady-state mapping exercise. An interim test report was submitted to DOE that includes the data taken by using GM chassis dynamometers. A Toyota Prius Data Exchange Workshop hosted by ANL took place at USCAR headquarters in Southfield, MI, in October 1999. The Workshop was well received by the 42 Government and Industry participants. Mike Duoba of Argonne made a presentation on the vehicle emissions, in-situ engine mapping, and the HEV control system and strategy used.

Test #	Cycle	Ph 1 MPG	Ph 2 MPG	Ph 3 MPG	Comp MPG	SOC-i	SOC-f
5898	CS FTP	58.33	59.84	66.39	61.20	71.4	71.9
5900	2 x HWY	84.05	84.62		84.34	68.1 / 69.1	69.1 / 67.6
5901	SC03	49.03				70.4	67.4
5904	CS UDDS	59.18	59.78		59.49	64.3	66.2
5905	Jap10-15	53.65				66.2	67.3
5906	US06	59.08				67.2	61.5
5907A	Engine Mapping	62.45				--	--
5907B	Engine Mapping	35.07				--	--
5907C	Engine Mapping	21.11				--	--
5907D	Engine Mapping	14.94				--	--
5907E	Engine Mapping	17.33				--	--
5907F	Transients	48.12					
5909	CS UDDS	54.06	55.40		54.75	36.5	55.8
5910	HS 505	62.85				55.7	56.9
5910	HS UDDS		65.92	50.70	59.97	56.9	57.9
5911	HS 505	62.87				57.9	59.2
5911	HS UDDS		65.49	49.80	59.42	59.2	60.7
5912	EUDC	52.64	72.15		63.52	60.2	59.6
5913	505 no Batt	61.10				--	--
5914B	55 MPH cruise	83.88					
5914A	35 MPH cruise						
5916A	Speed Sweep	42.66					
5916B	Speed Sweep	46.16					
6036	EUDC	52.61	76.58			69	67
6037	EUDC	51.23	76.13			60.9	69.4
6038	2 x HWY	87.26	87.52			67.4 / 67.4	67.4 / 66.9
6039	FTP	57.06	58.78		66.04	66.8	66.8
6041A	Load sweep	57.36				--	--
6041B	Load sweep	48.15				--	--
6041C	Load sweep	30.17				--	--
6041D	Load sweep	26.37				--	--
6041E	60 MPH	74.18				70.7	68.4
6041F	30 MPH	92.58				68.4	70

Honda Insight Test Results Using Automotive Testing Laboratory's Dynamometer

The 1999 Mercedes-Benz A-Class, A170 is significant in that it utilizes one of the first mass-produced common rail diesel engines in the world. The vehicle was outfitted with basic test probes normally utilized in chassis dynamometer vehicle emissions testing to measure pre- and post-catalytic converter emissions on a modal basis. Additionally, particulate measurements were taken. In February 2000, the vehicle was taken to the GM Vehicle Emissions Laboratory (GM-VEL) for emissions testing. The vehicle suffered equipment failure twice during earlier dynamometer testing. The front brakes failed during the first set of tests, and a front wheel bearing failed during the second set of tests. The cause of the failures was traced to the traction control/ABS system. This system was circumvented for the final test session. The vehicle underwent coastdown testing (both on road and on the chassis dynamometer) at GM-VEL to determine the horsepower setting to use during emissions testing. The vehicle was subjected to three each Federal Urban Dynamometer Driving cycle tests (FUDDS), Highway Fuel Economy tests (HWFET) and European EEC Type 1 tests. Testing is complete, and the final report was submitted to DOE.

The Honda Insight is the first HEV available in the United States. The vehicle is extremely lightweight because of the extensive use of aluminum and has a three-cylinder engine with an integrated motor assist (IMA) that also acts as a starter/alternator. The Honda Insight was zero-mile-emission tested by Honda, North America, at its Torrance, California, facility and underwent mileage accumulation at its Mohave Desert Proving ground. Following that testing, Honda conducted 4,000-mile emissions testing in California and Michigan prior to shipment of the vehicle to the dealer. After some initial testing at ANL, the vehicle was taken to Automotive Testing Laboratory (ATL) in Ohio. Several different aspects of the Insight were studied during vehicle testing. The vehicle control strategy, engine operation, regenerative braking, energy management, efficiency, and emissions were targeted. To generate the necessary data, the vehicle was driven over U.S. and European test cycles. Also, specific cycles were created to examine different areas of vehicle operation. Testing was completed, and a wide range of parameters was collected with a data acquisition system while the vehicle was tested on a chassis dynamometer. Standard test cycles and some custom transient and steady-state test cycles were used to collect data over a variety of operating conditions. These data streams allowed ANL to understand the hybrid system, battery management, and engine efficiency.

The Science Lab in Dearborn, Michigan, disassembled the Ford P2000 powertrain, which has a damaged flywheel/rotor assembly of the starter/alternator system. Ford engineers are working to solve this design flaw. The P2000 is expected to be back at ANL in November 2000, and vehicle testing will begin.

A 2001 model year Toyota Prius was received at ANL in August 2000. Mileage accumulation to age the catalyst and break-in the engine began and the accumulation report follows.

Date	8/00	8/00	9/00	9/00	9/00	9/00	9/00
Odometer (Miles)	928	1372	1827	2287	2357	2625	3075
Fuel Added (Gallons)	10.36	9.10	9.82	10.1	N/A	1.90	9.61
Fuel Economy (MPG)	?	48.9	46.3	45.5	N/A	N/A	46.8
Fuel Range (Miles)	?	444	455	460	N/A	N/A	450
Crankcase Oil Level	Full	Full	Full	Full	Full	Full	Full

Conclusions

The APTF plans to continue testing of high-efficiency electric motors, engines, transmissions, and vehicles, paying particular attention to powertrain control strategy development for increased fuel economy and reduced emissions. Testing will focus on vehicles, engines, and other HEV components (such as batteries, motors, and transmissions) of immediate interest to OAAT. The deliverable for each test is the raw and analyzed data with a summary report outlining the test methods and procedures. Performance figures and maps will be generated for incorporation into PSAT and ADVISOR component models. The vehicles will be tested by using the APTF chassis dynamometer facilities. Some vehicles may be sent to off-site electric chassis dynamometer facilities for baseline correlation and to perform tests that require an electric dynamometer.

Publications/Presentations

Duoba, M.J., et al., 2000, "Issues in Emissions Testing of Hybrid Electric Vehicles," *Global Powertrain Congress*, Detroit, MI, May 6–8.

IIIE. SIDI Development

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Objectives

- Investigate and position spark ignition direct injection engines (SIDI) as a viable powerplant for HEV applications
- Investigate the applicability of a laser-based polar nephelometer for measuring the extremely small particulates from SIDI engines
- Perform testing of an SIDI single cylinder engine to gain insights into the effects of the combination of various bulk air flows, fuel injectors, and fuel properties on efficiency and transient emissions critical to HEV operation
- Investigate the feasibility of the axially stratified CCFI engine

Approach

- Two identical Quad 4 research engines will be set up: one at ANL and the other at University of Texas (UT), Austin. Initially, the two engines will be tested using the same fuels and under identical operating conditions with identical RPECs (rapid prototyping engine control system). Once the two engines are well correlated, separate tests will be conducted to meet the different research objectives. ANL will concentrate on research in engine efficiency and transient emissions, and UT will continue fuel property studies

Accomplishments

- Advanced Engine Controls subcontract to UT continue. The second SwRI RPECS is being installed on UT's Quad 4 engine to allow verification and provide a common research platform for future SIDI HEV investigations

Future Direction

- Funding for this project will be shifted to the SIDI program managed by Rogelio Sullivan in FY01

Introduction

In FY98 and 99, the Toyota D4 engine, which represented state-of-the-art SIDI technology, was subjected to testing, mapping, and fuel studies. Six fuels with different volatility and hydrocarbon structure were tested, and several SAE papers were prepared regarding the comprehensive testing and effects of fuel composition on emissions and performance. ANL also awarded UT with an Advanced Engine Controls Subcontract to develop two modified engines with single cylinders converted to SIDI configuration. These engines allow investigation of the trade-offs between in-cylinder bulk airflow and fuel injector characteristics on transient emissions and SIDI engine efficiency.

Approach

The Advanced Engine Controls subcontract to UT continues. This development activity requires a powerful and flexible engine controller. The SwRI RPECS will be installed on a Quad 4 SIDI research engine (one cylinder converted to SIDI) built for ANL. The RPECS allows independent control of the fuel injection and timing, as well other key engine parameters.

Results

The second SwRI RPECS is being installed on UT's Quad 4 engine to allow verification and provide a common research platform for future SIDI HEV investigations. ANL is assessing the potential benefits of using SIDI for hybrid-electric vehicles. The assessment is focused first on fuel economy and emissions, which requires comprehensive measurement of the particulate emission. Currently, there is no measurement technique available, therefore, ANL is investigating the applicability of a laser-based polar nephelometer for measuring the extremely small particulates from SIDI engines. UT has worked with laser diagnostics in the past and is working with ANL in commissioning the nephelometer. UT is obtaining data on particulates emitted from a steady-state acetylene burner, quantifying the system response to mass concentration of particulates, creating absolute particle mass calibration, quantifying the system response to particulate size variation, obtaining preliminary particulate emission data from a research direct-injection spark-ignition engine, designing and constructing a short-residence-time sampling system to allow cycle-resolved particulate emission measurements in production direct injection engines, and providing a final report. The most recent research shows that preliminary particulate measurements collected by using the nephelometer system were attempted with exhaust from a single-cylinder research engine with a new direct-injection engine head. When the engine was running on propane, there was little signal obtained, probably because of the low particulate emissions. The data collected, however, showed very good correlation to the theoretical calculations of particulate density. When conventional gasoline was used, the particulate concentration was so high that the signals were saturated. Therefore, it appears necessary to incorporate a dilution system for the engine exhaust to keep it from swamping the digital camera.

Conclusions

The subcontract to UT will be completed early FY01.

Publications/Presentations

Ng, H.K., et al., 2000, "Effect of Fuel Parameters on FTP Emissions of a 1998 Toyota with a Direct Injection Spark Ignition Engine," *CEC/SAE Spring Fuels & Lubricants Meeting &Exposition*, Paris, France, June 21.

Ng, H.K., et al., 2000, "Effect of Fuel Parameters on Speciated Hydrocarbon Emissions from a Direct Injection Spark Ignition Engine," *CEC/SAE Spring Fuels & Lubricants Meeting & Exposition*, Paris, France, June 21.

Ng, H.K., et al., 2000, "Effect of Fuel Parameters on Emissions from a Direct Injection Spark Ignition Engine During Constant Speed, Variable Load Tests," *CEC/SAE Spring Fuels & Lubricants Meeting & Exposition*, Paris, France, June 21

IIIF. Model Development Support

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Objectives

- Develop advanced neural network- (NN-) based component models for more accurate vehicle simulations
- Control strategy optimization routines with the application of neural networks
- Explore fuzzy logic decision and control techniques

Approach

- Training a NN requires an engine to be run through a comprehensive learning profile by using actual test data. Model inputs and outputs required by the model are measured throughout the test. These inputs and outputs are fed into a neural network structure designed for engines, and a model is generated. Once the NN is established, we can feed new inputs into the NN model, and it will be able to accurately predict outputs. These outputs can be compared with actual test results for fine-tuning and validation of the model

Accomplishments

- A 1-Hz neural network model of the Prius engine was completed for engine outputs of power, torque, and the emissions of HC, CO, CO_2, and NO_x on the basis of GM Milford data

Future Directions

- ANL will continue NN development projects and apply them to both PSAT and ADVISOR, as well as expand efforts to include engines of interest, such as a SIDI engine
- ANL will continue development of neural and fuzzy logic control and optimization techniques
- Beyond FY01, applications of NN in component and system-level control will be explored

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Introduction

Current engine modeling techniques are not as robust as they should be to predict emissions and fuel consumption, especially for transient and start-up operation. The application of neural networks to predict engine behavior may be the solution to the limitations in current look-up table-based engine models. Training a NN requires an engine to be run through a comprehensive learning profile using actual test data. Model inputs and outputs required by the model are measured throughout the test. These inputs and outputs are fed into a neural network structure designed for engines, and a model is generated. Once the NN is established, we can feed new inputs into the NN model, and it will be able to accurately predict outputs. These outputs can be compared with actual test results for fine-tuning and validation of the model. Further, the NN control approach can be used to actively perform engine control in real time, minimizing emissions while maximizing efficiency.

Approach

ANL will acquire sufficient engine data sets, define NN structures, and train the models. The engines involved in FY00 are the 1.7 L common-rail CIDI engine provided by DOE/ANL, and the Prius 1.5 L port fuel-injected, spark-ignition engine. The NN model of the engine's emissions and fuel economy will be able to substitute for current engine models in ADVISOR and PSAT. ANL will also investigate by using NN engine models to actively control various engine-operating parameters in real-time. Ultimately, the neural network can be expanded to encompass the control of an entire HEV powertrain, a much more difficult task, but one that has the potential of being able to actively optimize HEV system performance over a wide range of operating profiles. We will endeavor to implement both the modeling and engine control applications for neural net technology.

ANL staff will also investigate another powerful tool to improve DOE's ability to develop and model optimized HEV control strategies. There are various parameters used in controls of a HEV system that can be adjusted to yield an altered outcome. Fuzzy logic and other advanced algorithms and models can be used to control the operation of the various components to provide improved performance. Trade-offs in emissions and efficiency are given various weighting ratios, and a smart controller can find the best path to achieving the prescribed goals. In FY01, these techniques will be applied to a working powertrain and computer models to predict performance of various new components and configurations.

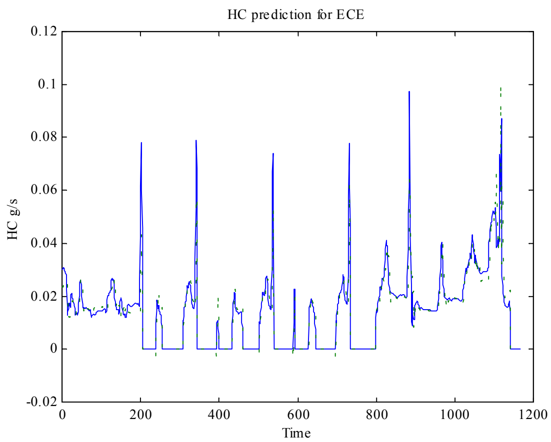
Results

A 1-Hz neural network model of the Prius engine was completed for engine outputs of power, torque, and the emissions of HC, CO, CO_2, and NO_x on the basis of GM Milford data. This provided the basis for beginning the creation of a 10-Hz version using ANL fast data that is now in progress for engine out power, torque, and engine block coolant temperature. To assist with the overall Prius vehicle model, a preliminary NN model of the Prius engine controller was created.

Work had begun on a NN structure specifically for turbo-charged CIDI engines. The data collection and training are optimized to provide accurate predictive engine torque outputs, fuel usage, and emissions. This development will be applied to the 1.7 L MB CIDI engine by using ANL's low-inertia dynamometer.

Conclusions

ANL will continue NN development projects and possibly expand the work by incorporating NN-based adjustments to other component models. Applications of NN in component and system-level control will be explored. ANL will also continue development on neural and fuzzy logic control and optimization techniques.



Predicted (solid) Versus Measured Results (dashed) of Hydrocarbon Emissions from Prius 1.5 L

ANL will continue NN development projects and apply them to both PSAT and ADVISOR as well as expand efforts to include engines of interest, such as a SIDI engine. ANL will continue development of neural and fuzzy logic control and optimization techniques. If the NN modeling is as successful as it appears it will be, we propose to possibly expand this leading-edge effort by incorporating NN-based adjustments to other component models. Beyond FY01, applications of NN in component and system-level control will be explored.

Publications/Presentations

SAE Congress 2000 paper, Feb. 2000.

IIIG. PSAT PROTOTYPING

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Objectives

- Develop a toolkit capable of going from modeling to prototyping by developing an integrated toolkit by using PSAT (PNGV System Analysis Toolkit), the modeling software, and PSAT-PRO, its companion prototyping software

Approach

- Develop the best control strategy by using PSAT and incorporate it into a vehicle controller by using PSAT-PRO. With PSAT-PRO, users are able to control their prototypes in real time by using their own control strategy developed in PSAT
- PSAT-PRO has been designed to calibrate component models. In fact, our test methodology is based on difference analysis between simulation results and test data. Since we use an integrated toolkit, we can go back in simulation and modify the model until simulation results reach test data
- With PSAT-PRO, we have the ability to control a dynamometer to simulate vehicle behavior. In this way, we can test only one component of the hybrid powertrain in the same configuration and conditions as if it were in a vehicle

Accomplishments

- The result of this project is a software highly linked to PSAT, while generic enough to go from modeling to prototyping for any kind of hybrid configuration. PSAT-PRO prototyping software gives the opportunity to analyze a hybrid system by different ways: Real Time Simulation, Hardware In the Loop (HIL), and Rapid Prototyping

Future Directions

- Control a hybrid configuration on a test stand composed by a motor, an engine, and a CVT by using PSAT-PRO
- Using HIL principle, we plan to test an engine on a test stand controlling a low-inertia dynamometer to simulate a HEV's behavior
- Improve our post-processing tools and maximize the linkage with PSAT

Introduction

One of the goals of the Program for a New Generation of Vehicle (PNGV) is to develop a toolkit capable of going from modeling to prototyping. To reach this goal, ES/CTR developed an integrated toolkit by using PSAT (PNGV System Analysis Toolkit), the modeling software, and PSAT-PRO, its companion prototyping software. PSAT-PRO has been designed to be able to control any kind of HEV or hybrid powertrain on a test stand. PSAT-PRO enables hardware-in-the-loop (HIL) testing, as well as full systems control capability, and provides valuable data for PSAT validations and HEV control system development.

Approach

Argonne's approach is to develop the best control strategy by using PSAT and to incorporate it into a vehicle controller by using PSAT-PRO. With PSAT-PRO, users are able to control their prototypes in real time by using their own control strategy developed in PSAT.

PSAT-PRO has also been designed to calibrate component models. In fact, our test methodology is based on difference analysis between simulation results and test data. Since we use an integrated toolkit, we can go back in simulation and modify the model until simulation results reach test data.

Hybrid Powertrain on a Test Stand Controlled by PSAT-PRO

With PSAT-PRO, we have the ability to control a dynamometer to simulate vehicle behavior. In this way, we can test only one component of the hybrid powertrain in the same configuration and conditions as if it were in a vehicle.

Results

The result of this project is a software highly linked to PSAT, while generic enough to go from modeling to prototyping for any kind of hybrid configuration. PSAT-PRO prototyping software gives the opportunity to analyze a hybrid system by different ways:

- Real Time Simulation:
  The vehicle system controller and the HEV model are downloaded on two different electronic boards, communicating together. In this way, the vehicle model reacts in real time, exactly like the actual system. This phase can be very useful to tune the controller.
- Hardware-In-the-Loop:
  With PSAT-PRO, we have the possibility to test a hybrid powertrain component by component in the vehicle configuration by simulating the rest of the vehicle with the dynamometer.
- Rapid prototyping:
  Rapid prototyping is the capability to integrate the system control model in the vehicle's control unit. So, we have the capability to perform a test, analyze the results, improve the controller, and perform the same test again. With PSAT-PRO, it is so easy to download the control scheme that it can be useful to fine-tune the controller by taking into account results that can only be provided by test data. For instance, we can optimize a HEV control strategy to reduce the vehicle's emissions.

The Unique Mobility motor-only configuration was the first component tested in the prototyping development phase. ANL staff developed a generic structure for the control command system in order to reuse it for other configurations. In order to validate the control command system, we perform a simulation by using a test stand model. With PSAT-PRO, we have the capability to simulate the test procedure, which will be used to control the component on the bench. The test stand can be controlled by using the dynamometer speed regulation, but in order to simulate the vehicle behavior with the dynamometer, we also want to be able to control it in torque. In fact, we can control the system with a motor speed regulation, and we can evaluate the vehicle torque losses at this regulated speed to command the dynamometer. ANL staff set up the speed regulation to represent driver behavior by using the PSAT-PRO simulation capability.

Work continues on the Prototyping drivetrain using a Mercedes 1.7 L CIDI engine, modified transaxle, clutch, a Unique Mobility 40-kW electric motor, and a Nissan CVT. Component adapters were fabricated, and mounting hardware was ordered. Design and fabrication of driveline couplings and mounting components for the powertrain continued. A driveline brake is being specified. Extensive machining to the Nissan CVT continued. The machining will eliminate the torque converter and accommodate an external oil pump and control of the CVT sheaves using a servomotor. An HBM torque sensor is being integrated into the bellhousing of the CVT.

Conclusions

ES/CTR plans to control a hybrid configuration on a test stand consisting of a motor, an engine, and a CVT in FY01 by using PSAT-PRO. Using the HIL principle, we plan to test an engine on a test stand controlling a low-inertia dynamometer to simulate a HEV’s behavior. We also want to improve our post-processing tools and maximize the linkage with PSAT.

IIIH. PSAT MODEL MAINTENANCE AND CUSTOMER SUPPORT

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Objectives

- Support further simulation in vehicle development
- Develop flexible simulation tools
- Further develop the PNGV System Analysis Toolkit (PSAT) under the direction and contributions of Ford, GM, and DaimlerChrysler

Approach

- Model architecture is "forward-looking," meaning the component interactions are "real world"
- Method is computationally more intensive than "backward-looking" architecture; however, the result is a tool that will allow the advanced powertrain designer(s) to develop realistic control strategies and assess component behaviors in a system environment by using models closer to reality
- Models are developed using Matlab v5.3 and Simulink v3

Accomplishments

- Refined, validated, and integrated PSAT to allow the users to simulate more than a hundred configurations, develop control strategies, implement directly and test at the bench scale or in a vehicle, and run several simulations in a row in a short amount of time
- From PSAT V2.0 to PSAT V3.0
- Reorganized PSAT to be generic and reusable by:
  - Building each drive train accordingly to user choices
  - Having the possibility to compare several control strategies within the same powertrain controller using switches
  - Having a generic component model format (3 ins/3 outs)
  - Consolidating and streamlining over 2500 variables and parameters
  - Parameterizing the software
  - Modifying PSAT to facilitate the integration of new data file and component models
  - Included a voltage bus (crucial for motors and batteries)
  - Increased the number of configurations (over one hundred)
- Improved transient phase behavior (engine starting, clutch engagement / disengagement) by:

  - Creation of new starter and clutch models
  - Modification of engine and transmission models
  - Creation of new control strategies to better handle transients
  - Creation of specific control strategies for performances purposes
- Released PSAT V3.0 in May 2000 and held training in Detroit the same month
- From PSAT V3.0 to PSAT V4.0
- Created a new Graphical User Interface (GUI) by using the original GUI
- Created 54 files, modified or wrote 28 files, kept 3 files
- Incorporated main new features (most of them could be included in ADVISOR)
- New initialization window (more component, versioning, type, etc.)
- Possibility to run may simulations in a row (different cycles, parametric study, SOC equalization, etc.) as each simulation is saved
- Possibility to access all the results from all the simulations
- Sped up the simulation time by a factor >6 by using a compiled version (Use C code instead of Simulink)
- Identified possibility to change a parameter or a cycle without recompiling
- Added conventional 4WD configurations
- Added new post-processing capabilities
- 4 phases (acceleration/deceleration and charging/discharging) – initially only two
- Information on energy, power, torque, speed, current, and voltage – initially only energy
- Released PSAT V4.0 in October 2000 and a held training in Detroit in December
- Validated the Japanese version of the Toyota Prius by using a new procedure dedicated to hybrid vehicles
- Integrated a new engine model (MEEM) to better take emissions into account (multi-year, multi-million-dollar program that has been peer reviewed and has more than 300 engine maps available)
- Provided ongoing user support and maintenance
- Attended and presented PSAT information at the GPC 2000 in June in Detroit and at NREL's User's Meeting
- Completed full integration of the GUI
- Created a mission statement and identified PSAT customers
- Developed and distributed a satisfaction survey, evaluating the results

As a result, more than 30 people now use PSAT. DaimlerChrysler currently integrates its Durango model into PSAT, while General Motors is doing the same thing with the Precept. Discussions will be under way for the HEV Ford Escape.

Future Directions

- ES/CTR plans to not only extend PSAT capabilities by adding new drive train configurations (e.g., parallel 4WD), new control strategies, and new models, but also increase its flexibility and reusability, which are two key characteristics of PSAT
- The number of users will be increased through use in universities and with key suppliers
- Public version of PSAT will be released on the Internet

Introduction

In a world of growing competitiveness, the role of simulation in vehicle development is constantly increasing. Because of the number of possible hybrid architectures, the development of a new generation of vehicles will require accurate, flexible simulation tools. Such a simulation program is necessary to quickly narrow the technology focus of the PNGV to those configurations and components that are best suited for achieving these goals. ES/CTR undertook a collaborative effort to further develop the PNGV System Analysis Toolkit (PSAT) under the direction and contributions of Ford, GM, and DaimlerChrysler.

Approach

The model architecture is "forward-looking," meaning that component inter-actions are "real world." This method is computationally more intensive than "backward-looking" architecture; however, the result is a tool that will allow the advanced powertrain designer(s) to develop realistic control strategies and assess component behaviors in a system environment by using models closer to reality. These models are developed by using Matlab v5.3 and Simulink v3.

Results

PSAT allows the user to simulate more than a hundred configurations (conventional, series, parallel, and power split) while giving users the ability to choose appropriate configuration, depending on customer expectations. PSAT is well suited for development of control strategies, and by using accurate dynamics component models as its code, PSAT can be implemented directly and tested at the bench scale or in a vehicle by using its extension for prototyping PSAT-PRO. PSAT also allows users to run several simulations in a row in a short amount of time using a compiled version. Proprietary and non-proprietary versions PSAT 4.0 was distributed to PNGV research partners in November 2000.

The PSAT forward-facing vehicle simulation software has been developed and refined over the last few years, with increasing functionality and user base. ANL is making the modifications necessary to allow the new common GUI (based upon ADVISOR's GUI) to account for PSAT specificities. Additionally, more sophisticated analysis is required to satisfy the PSAT analysis and trade-off study requests. Simulation programs are ultimately a tool to better serve customers. A clear understanding of "who is the customer" is mandatory. Regular measurement of customer satisfaction is done to maintain proper program perspective and direction. Systems approach for meeting the Goal 3 objective for PNGV requires coordination of performance and cost targets of various component tech teams. PNGV systems analysis is critical to analyzing vehicle-engineering trade-offs and to setting the performance and cost priorities of subsystem technologies. Effective design support to the PNGV technical teams is provided through the creation of detailed, rigorous cost and design reliability models to support ongoing technology selection. These models are continuously upgraded as new information becomes available.

Conclusions

ANL will continue to support and improve PSAT for use by the expanding user base to various PNGV technical teams and national laboratories, with developmental support from industry and universities. ANL will identify potential PSAT customers and then how to serve the specific customers of the PSAT vehicle simulation programs best. ANL will also continue to work with Oakland University in the area of optimization and control. While much progress has been made in these areas, more work is needed to more fully integrate optimization into the analysis tools used by the systems analysis team.

Publications/Presentations

Pasquier, M., and Rousseau, A., “PSAT and PSAT-PRO: An Integrated and Validated Toolkit from Modeling to Prototyping”, SAE paper 01-P178.

Rousseau, A., and Pasquier, M., “Validation Process of a HEV System Analysis Model: PSAT”, SAE paper 01-P183.

An, F., and Rousseau, A., “Integration of a Modal Energy and Emission Model into a PNVG System Simulation Model: PSAT”, SAE paper 01.

Rousseau, A., and Larsen, R., “Simulation and Validation of Hybrid Electric Vehicles using PSAT”, GPC conference, Detroit, June 6 - 8, 2000.

IIIi. COMMON OPTIMIZATION AND CONTROL TOOLS

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Objectives

- Investigate existing optimization algorithms, develop new robust and efficient optimization algorithms, and evaluate their effectiveness for both PSAT and ADVISOR
- Continue investigating several control and energy management strategies, taking into the account the dynamic behavior of the subsystems

Approach

- Revisit the different optimization algorithms that have already been used and investigated for both PSAT and ADVISOR
- Develop a survey of different optimization methods that have the greatest potential for robust and efficient search for the global optimum
- Investigate and test global optimization algorithms in terms of efficient computation and robustness
- Change the different available controllers in PSAT to digital controllers
- Incorporate the effect of the transients in the components to help evaluate driveability issues

Accomplishments

- Evaluated previous optimization and control work and selected future algorithms
- Formulated an optimization and control problem for a specific vehicle configuration
- Integrated the optimization algorithms with PSAT for the parallel configuration
- Developed and integrated the control system with PSAT

Future Directions

- Further investigate existing optimization algorithms and develop new robust and efficient optimization algorithms (as necessary) and evaluate their effectiveness for PSAT
- Continue investigating several control and energy management strategies, taking into account the dynamic behavior of the subsystems

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Introduction

Since 1996, the SATT has been working with U. of Michigan (UM) and Oakland University (OU) in the area of optimization and control, and over the past year, NREL has been working with Vanderplaats Research and Development (VR&D) in the area of optimization of control strategies and component sizing. While much progress has been made in these areas, more work is needed to more fully integrate optimization into the analysis tools used by the systems analysis team.

Oakland University developed different energy management strategies for series and parallel hybrid vehicles. Those strategies were the basis for the energy management strategies that are currently in PSAT. The work at OU also helped in debugging and testing of the software. Phase II of the project is concentrating on using fuzzy control for the energy management strategies of parallel hybrid vehicles. The energy management strategies currently being developed are implemented as a discrete control system. In future work, we are looking to continue devising combined optimization of energy management and sizing of hybrid vehicles. The energy management and control strategies will also take into consideration the dynamic behavior of the components during control evaluation. Digital controllers will be designed and evaluated in the OU strategy to support hardware-in-the-loop activities.

The objectives of this project are to investigate existing optimization algorithms, develop new robust and efficient optimization algorithms (as necessary), and evaluate their effectiveness for both PSAT and ADVISOR. Another objective of this task is to continue investigating several control and energy management strategies, taking into account the dynamic behavior of the subsystems. Discrete control systems that will support the hardware-in-the–loop activities will be emphasized.

Approach

In the technical approach, the different optimization algorithms that have already been used and investigated for both PSAT and ADVISOR will be revisited. The advantages and disadvantages of each approach will be discussed. A survey of different optimization methods that have the greatest potential for robust and efficient search for the global optimum will be developed. Global optimization algorithms, in particular, will be investigated and tested in terms of efficient computation and robustness. Candidates for global optimizations are DIRECT, generic algorithms, and simulated annealing. The optimization tool should allow the user to choose parameters for the several components and control. The user can also define a fuel economy objective function with emission and performance constraints.

In the technical approach for the control and energy management strategies, the different available controllers in PSAT will be changed to digital controllers. This improvement will give more realistic performance and it will support the hardware-in-the loop activities. The controller's evaluation, will also incorporate the effect of the transients in the components which will help in the evaluation of driveability issues.

Results

ANL and OU evaluated the previous optimization and control work and selected future algorithms, formulated an optimization and control problem for a specific vehicle configuration, integrated the optimization algorithms with PSAT for the parallel configuration, developed and integrated the control system with PSAT, tested the optimization and control, and generated results

Conclusions

Oakland University developed a control strategy and incorporated it into PSAT on the basis of fuzzy logic to optimize the drivetrain, while the UM developed a generic global optimization algorithm that will be incorporated into PSAT and ADVISOR. Both of these universities will continue to enhance their control algorithm and optimization to improve drive train efficiency and decrease emissions. Tests at the ANL Advanced Powertrain Test Facility (APTF) using PSAT-PRO will allow UM to validate and improve their assumptions.

IIIJ. Variable Compression Ratio Engine Technology

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Objectives

- Develop a VCR engine having comparable cost to today's production engines, capable of achieving U.S. Tier 2 and California LEV-II emissions certifications, and an efficiency great enough for achieving a passenger car fuel economy of 80 mpg

Approach

- Use an exceptionally small displacement engine to achieve high energy conversion efficiency at low power levels

- Supercharge and intercool the engine to achieve high specific power levels, and to attain PNGV performance targets

- Use variable compression ratio to prevent engine knock at high power levels, and to substantially improve engine efficiency at low power levels

Accomplishments

- Computer modeling determined that the projected efficiencies for the VCR Engine would result in the attainment of the Partnership for a New Generation of Vehicles (PNGV) goal of 80 miles per gallon in a PNGV-type vehicle. Dynamometer tests of the proof-of-concept VCR engine at AVL Powertrain validated efficiency predictions made by the computer model

- Other findings from the AVL Powertrain tests include:

- VCR engine exhibited a very favorable burn rate and coefficient of variance allowing the application of lean burn and/or EGR dilution technology to further improve efficiency

- Preliminary evaluation of hydrocarbon and nitrogen oxide emission levels yielded results favorable and consistent with expectations for a gasoline engine of similar power output

Future Directions

- Design, source, and build a fully functional VCR mechanism and test in a prototype engine

- Test, calibrate, and refine the prototype VCR engine and associated emission control systems through dynamometer testing and in-vehicle simulation

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Introduction

OAAT is sponsoring research on variable-compression-ratio (VCR) technology with supercharging to significantly improve spark-ignition engine efficiency while achieving low emissions using proven 3-way catalyst emission control technology.

A fuel economy of 81 mpg was projected for a PNGV-intent vehicle powered by a simulated spark-ignition gasoline VCR engine. A stoichiometric ($\lambda = 1$) air/fuel ratio was employed to provide high certainty of achieving U.S. Tier 2 and California LEV-II emissions certification. VCR technology offers the potential for attaining diesel-like fuel efficiency while achieving future federal and state emission regulations using proven emission-control technology, even with today's sulfur-containing gasoline (ultra-low-sulfur gasoline not required). The VCR engine also shows potential for rapid commercialization at a competitive cost.

How the Technology Works

VCR and small engine displacement are used to achieve high energy conversion efficiency at low power levels. As illustrated in Figure 1, high efficiency at low power levels is important for achieving high vehicle mileage because automobile engines operate at low power levels most of the time. Supercharging and intercooling are used to achieve high power levels from the small engine. VCR is used to prevent knock at high power levels (with a low compression ratio) and to improve efficiency at low power levels (with a high compression ratio). Stoichiometric three-way catalyst technology is used to achieve emission requirements, so ultra-low-sulfur fuel is not needed. The spark-ignition port-fuel-injected VCR engine operates efficiently and cleanly on gasoline and a range of alternative fuels.

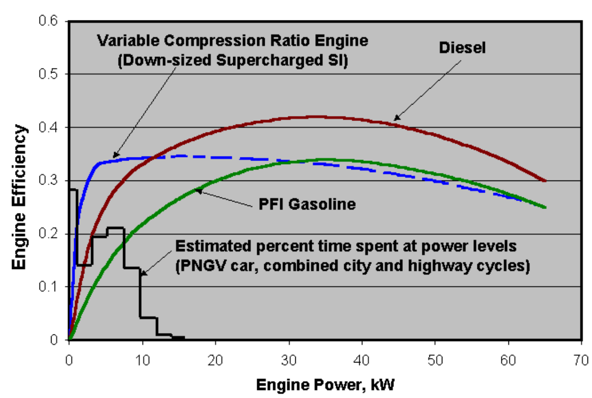

Figure 1 – Variable compression ratio engine promises high efficiency at low engine power levels

Approach

Ricardo Inc. estimated the efficiency of the VCR engine using its WAVE gas-dynamic computer software and in-house data on engine friction levels. Using a second computer code, CYSIM, Ricardo then estimated vehicle mileage for a PNGV-intent vehicle body equipped with the simulated VCR engine. The simulated vehicle included a 6-speed automated manual transmission. The vehicle was assumed to have an alternator that captures braking energy for powering accessory loads. In order to minimize projected vehicle cost, the vehicle, as simulated, was assumed not to have an electric only drive. A fuel economy of 81 mpg was projected for the vehicle.

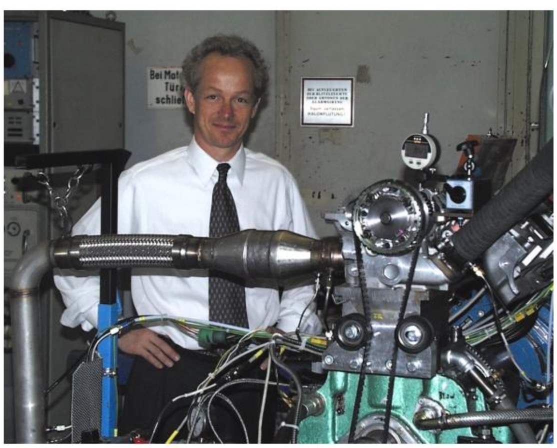

Figure 2 – Principal Investigator Charles Mendler and the VCR development engine at AVL Powertrain in Austria

A single-cylinder development engine was designed and built to validated Ricardo's engine efficiency projections, investigate combustion stability, and determine maximum compression ratio capacity at various engine loads. In the development engine, compression ratio was adjusted with shims of various thickness, which raised the height of the cylinder head. Computer Systems Management Inc. (CSMi) was responsible for overall project management, and the design and procurement of the engine's cylinder head, pistons, and connecting rod. AVL Powertrain Inc. was responsible for the engines cranktrain and testing. The dynamometer tests at AVL validated Ricardo's computer model projections of engine efficiency. State of the art combustion burn rates were achieved, and engine out emission levels were favorable.

Results

A combined EPA city/highway fuel consumption of 81 mpg was projected for a PNGV-intent vehicle with a small displacement port-fuel-injected VCR engine equipped with on-demand supercharging, an automated manual 6-speed transmission.

The engine operates at stoichiometric air/fuel ratio throughout the FTP city and highway drive cycles, giving it a high probability for meeting current and future federal and state emission standards using three-way catalyst based aftertreatment systems (ultra-low sulfur fuel not needed).

All vehicle gradeability, acceleration, and maximum speed targets can be met with the downsized supercharged VCR engine with no electric motor assist.

Findings from the dynamometer tests include:

- Engine efficiency goals were effectively achieved,
- Engine volumetric efficiency and power are slightly higher than estimated by Ricardo,

- Knock-limited compression ratio is about 1.5 points higher than estimated by Ricardo at light torque levels,
- Coefficient of variance (COV) values are ~1.0 to 1.5% at MBT,
- Burn rates are between 25 and 30 crank angle degrees (2-90% burn),
- HC and NO_x emission levels appear favorable, and
- Lean burn and/or EGR dilution performance is expected to be good due to the fast burn rate and low COV. (Lean burn tests have not been conducted.)

Future Work

In the next phase of work, a fully functional VCR engine will be designed, sourced, and built. To reduce costs and shorten development time, the engines will employ a commercially available cylinder head. The engine will have a structural capacity for operation at 150 horsepower per liter, however, the initial build and testing of the engine will not include supercharging. The associated emission control systems will also be installed and calibrated through dynamometer testing and in-vehicle simulation.

IV. OAK RIDGE NATIONAL LABORATORY SUPPORT

IVA. Automotive System Cost Modeling

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Objectives

- Develop a stand-alone, system-level cost model of new generation vehicles to identify cost issues
- Develop a repository of cost data about various component-level technologies being developed today for new generation vehicles

Approach

- Bottom-up approach considered for the vehicle definition as five major subsystems consisting of total 36 components
- Performance and system interrelationships considered to estimate system and subsystem costs for calculating total vehicle cost
- Spreadsheet-based structure to provide "open" design and allow for future expansion

Future Directions

- Extensive data collection of current and emerging PNGV technologies
- Model validation through detailed comparisons of available concept vehicles and technology-representative components and subsystems

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Introduction

The automotive system cost model is being jointly developed in two phases by Oak Ridge National Laboratory and Ibis Associates, Inc., with work having been underway for more than a year. The first phase of model development has been completed and it focused on the development of a coherent framework for tracking and balancing the impacts of changes in designs and technologies of the major vehicle systems and subsystems.

Approach

Figure 1 shows a schematic block diagram of the cost model architecture, including its logic. The model estimates the total cost of ownership of new generation of vehicles based on cost estimates made at the level of five major subsystems consisting of a total of 30+ components, where each component represents a specific design and/or manufacturing technology. Cost, mass, and performance interrelationships were characterized for conventional vehicles and select advanced technologies of advanced powertrains and body concepts. These features of the model allow cost estimation to occur at any level, from the individual component to the total vehicle and allow for the determination of the best combinations of materials and technologies to achieve the target fuel economy at the least cost.

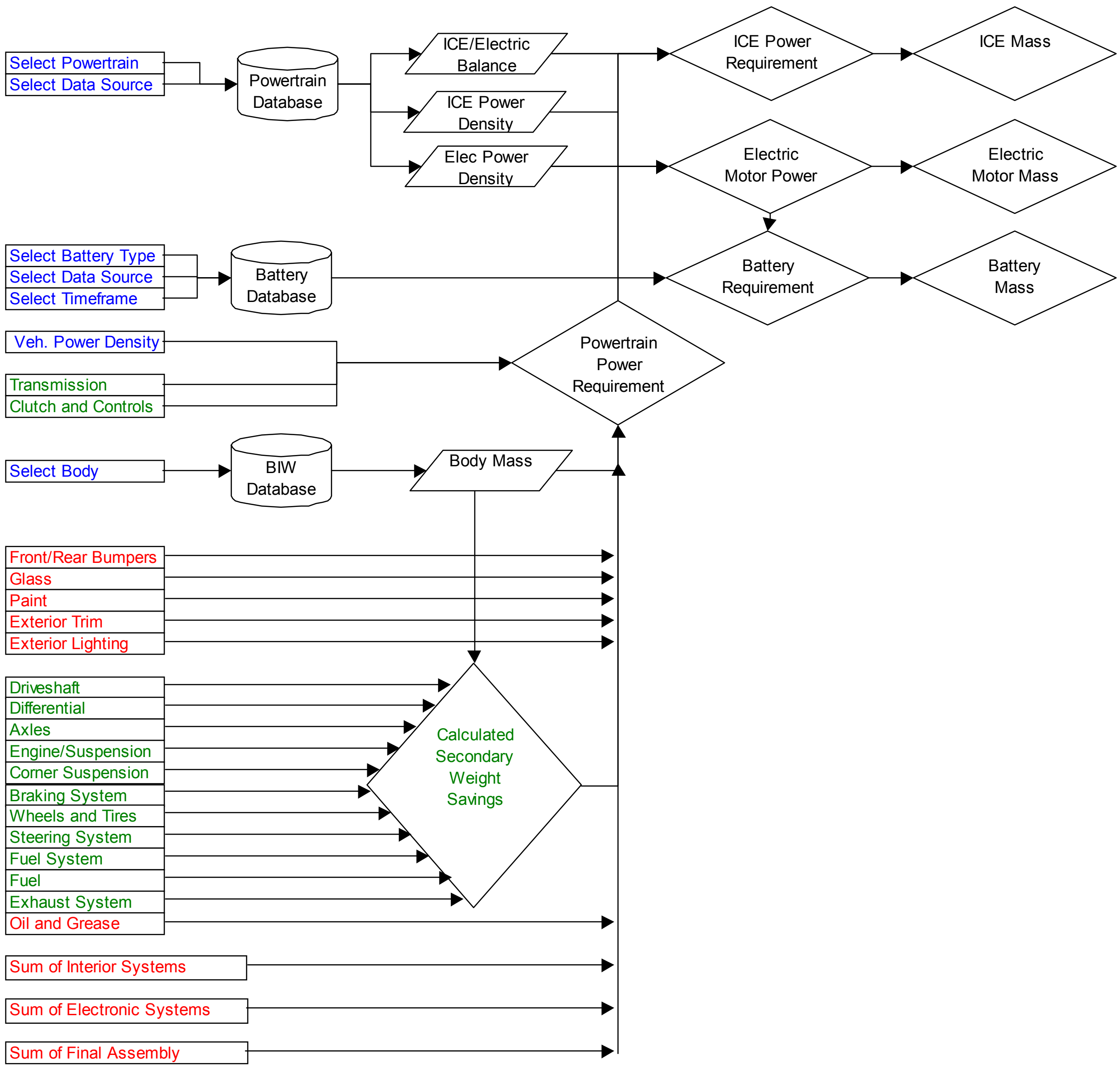

Figure 1: Cost model logic and structural definition

Results

Model logic and database structures were designed to allow the model to continue to grow and capture additional technology options and performance relationships as it is applied. Although the model is being developed as a stand-alone model that estimates costs based on the input performance parameters calculated by other models such as PSAT (PNGV Systems Analysis Toolkit) and Advanced Vehicle Simulator (ADVISOR) used by the PNGV system analysis technical teams for vehicle design, it can be included as a part of integration effort of these two performance models.

The model is implemented in numerous worksheets, each devoted to certain types of inputs or calculations. The layout and dataflow between the different sections of the model are shown in Figure 2. The use of an Excel spreadsheet design framework allows the ease of navigation among various subsystems and options. A user can examine two scenarios at a time, using either user-defined inputs at each system level or inputs predefined by the model. Model outputs include both tabular and graphical formats indicating a breakdown of the total ownership costs beyond the system manufacturing cost such as financing, insurance, fuel, maintenance, repair, and disposal. The model can be used to examine the effect of various body-in-white designs on the total ownership cost and to determine how aggressive cost targets by different subsystems need to be to achieve the PNGV cost goal.

The ongoing second phase of model development has been an intensive data collection effort to assemble and incorporate information characterizing advanced vehicle technologies from both demonstration- and conceptual-level programs. The data repository will provide a consistent and standard economic tracking of technology options and facilitate communication of system and vehicle strategies among development programs. Relative to conventional vehicle systems, this information is rather limited and more speculative, so efforts have been to identify the data points and relationships based on the published literature and on information obtained from participants currently engaged in this area of research. In a limited number of cases where technologies are at the pre-commercialization stage, actual cost estimates will be made using a separate simple modeling framework.

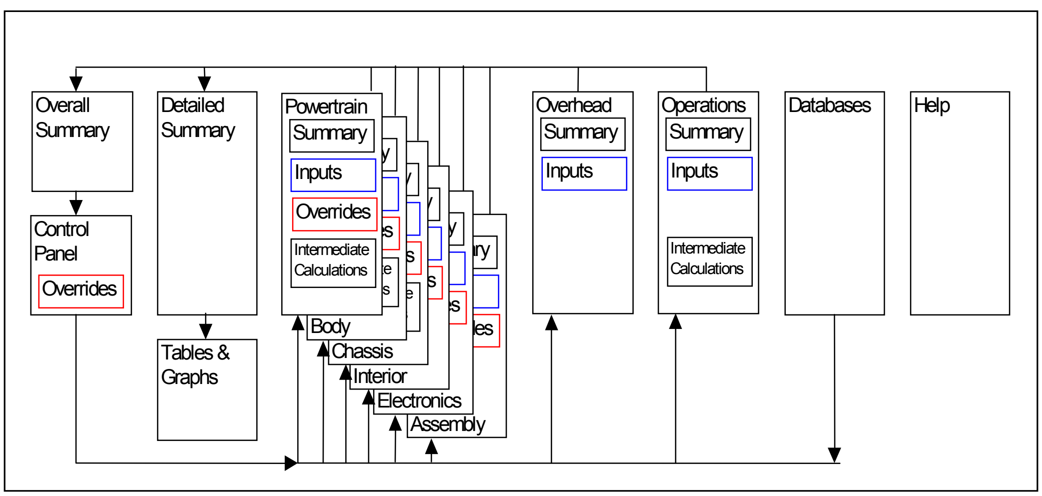

Figure 2: Automotive system cost model layout

APPENDIX A: ACRONYMS, INITIALISMS, AND ABBREVIATIONS

ADVISOR	Advanced Vehicle Simulator
ANL	Argonne National Laboratory
APTF	Advanced Powertrain Test Facility
ATL	Automotive Testing Laboratory
C	celsius
CARB	California Air Resources Board
CIDI	compression ignition direct injection
CO_2	carbon dioxide
CVS	constant volume sampler
CVT	continually variable transmission
DOE	U.S. Department of Energy
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ES/CTR	Argonne National Laboratory's Energy Systems/Center for Transportation Research
EV	electric vehicle
FUDDS	Federal Urban Dynamometer Driving Cycle Tests
FY	Fiscal Year
GM	General Motors
GUI	graphical user interface
HC	hydrocarbon
HEV	hybrid electric vehicle
HIL	hardware in the loop
HWFET	Highway Fuel Economy Tests
kW	kilowatt
LEV	low emission vehicle
MPG	miles per gallon
NiMH	nickel metal hydride
NiZn	nickel zinc
NN	Neural Network
NO_x	oxides of nitrogen
NREL	National Renewable Energy Laboratory
OAAT	Office of Advanced Automotive Technologies (DOE)
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
OTT	Office of Transportation Technologies (DOE)
OU	Oakland University
PbA	lead acid
PNGV	Partnership for a New Generation of Vehicles

PSAT	PNGV System Analysis Toolkit
QA	quality assurance
R&D	research and development
RPECs	Rapid Prototyping Engine Control System
SIDI	spark ignition direct injection
SULEV	super ultra low emission vehicle
SUV	sports utility vehicle
SwRI	Southwest Research Institute
TLEV	transitional low emission vehicle
ULEV	ultra low emission vehicle
UM	University of Michigan
USCAR	United States Council for Automotive Research
UT	University of Texas